

Navigation Strategy for the Galileo Jupiter Encounter and Orbital Tour: An Overview

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Galileo has successfully completed the Venus-Earth-Earth Gravity Assist (VEEGA) phase of the interplanetary transfer to Jupiter (Fig. 1), and the atmospheric Probe has been released on a trajectory targeted to the desired entry aimpoint. The remaining Orbiter spacecraft, after having successfully completed the Orbiter Deflection Maneuver (ODM), is now targeted to a 1000 km altitude Io flyby which occurs prior to Jupiter closest approach (Fig. 2). This gravity-assist flyby reduces significantly the propellant required for the Jupiter Orbit Insertion (JOI) maneuver. About 4.5 hours after the Io flyby, the Orbiter passes through Jupiter closest approach at a distance of 4.0 RJ (1 RJ = one Jupiter radius = 71,492 km).

Starting a few minutes later, the Orbiter will receive and store data transmitted from the Probe for 75 min as it descends through the Jovian atmosphere (Fig. 3). Shortly after the end of Probe data acquisition, the Orbiter performs the JOI maneuver slowing the spacecraft in order to enter orbit about Jupiter. The orbital phase of the mission, referred to as the "orbital tour", lasts two years. During this time, the Orbiter completes 11 orbits about Jupiter, 10 of which contain a close flyby of one of the three outermost Galilean satellites: Europa, Ganymede, and Callisto (Fig. 4). These "targeted" satellite encounters are at altitudes between 200 and 3000 km. In addition, on four of the 11 orbits, there is a second, more-distant satellite flyby. These "nontargeted" encounters range between 23,000 and 80,000 km. The satellite encounters are listed in Table 1. Navigation of the Jupiter approach/encounter and tour phases of the Galileo mission is a challenging task. Over a time period of slightly more than two years, there are 16 satellite encounters and 40 planned propulsive maneuvers for trajectory control.

The unavailability of Galileo's High-Gain Antenna which failed to open properly and the consequent reliance on the Low-Gain Antenna for communication with Earth has further complicated the navigation task. Certain orbit determination (OD) data types will not be available: two-way coherent Doppler data using an S-band uplink and an X-band downlink, range data using the onboard ranging hardware, and plane-of-the-sky position information from the Delta-Differential One-Way Ranging technique. There has also generally been a reduction in the total amount of navigation data that is available: S-band Doppler and optical navigation (OPNAV) pictures. Special OPNAV software has had to be developed to edit the OPNAV pictures onboard the Orbiter, thereby reducing the required amount of data to be transmitted to Earth for each picture.

The two primary data types for orbit determination are two-way coherent S-band Doppler and optical navigation (OPNAV) pictures taken with Galileo's camera showing the target body and one or more cataloged stars. The Doppler data provides range-rate information, and the OPNAV pictures provide positional information in a plane normal to the camera pointing direction. A limited amount of range information, derived from a newly-applied ramped-Doppler technique, is used during the Jupiter approach phase as a complementary data type in order to improve confidence in the OD results of the trajectory estimation process and to decrease slightly the uncertainties in the estimated Io encounter conditions used for Trajectory Correction Maneuver (TCM) design. The 1-sigma OD knowledge uncertainties in the Io B-plane for the last two critical navigation events prior to Jupiter arrival are:

<u>Event</u>	<u>Epoch</u>	<u>OD Deliver-v</u>	<u>B.R</u>	<u>B.T</u>	<u>TOF</u>
TCM-28A	Io-5 days	Io-6 days	28 km	53 km	4.3 sec
JOI Update	10-2 days	Io-3 days	27 km	15 km	0.6 sec

The 1-sigma OD knowledge uncertainties for the final pre-encounter OTM during the orbital tour are shown in Table 2.

Propulsive maneuvers are accomplished with the Galileo Retro-Propulsion Module (RPM) provided by the Federal Republic of Germany (Fig. 5). The RPM has 12 10-Newton thrusters used both for TCMS during Io/Jupiter approach and for Orbit Trim Maneuvers (OTMs) during the orbital phase of the mission and a single 400-Newton engine used for the three largest propulsive maneuvers: ODM, JOI, and the Perijove Raise Maneuver (PJR) which occurs at the first apojoave after JOI (Fig. 6). The 10-Newton thrusters used for TCMS and OTMS are mounted so as to enable velocity changes in either direction along the Orbiter spin axis (axial AV) and in any direction in a plane normal to the Orbiter spin axis (lateral AV). TCMS and OTMS can be performed either as vector-mode maneuvers, for which the spacecraft does not change orientation during the maneuver and axial and lateral AV components add to form the desired AV vector, or as turn/burn maneuvers, for which the spacecraft is reoriented so that the AV vector can be accomplished with either axial or lateral thrusters only. In the absence of Orbiter pointing constraints, the turn/burn mode is usually the optimal mode for all but extremely small AVS. There are four TCMS scheduled during the final Io/Jupiter approach phase, and typically three OTMS per orbit are planned in the orbital phase. Maneuver analysis and design has the following primary goals: ensure accurate delivery of the Orbiter to the each of the desired satellite encounter aimpoints in the presence of statistical trajectory dispersions, generate mission AV statistics, and minimize propellant consumption. For each TCM/OTM, Table 3 shows the location, target body, and predicted delivery accuracy, and Table 4 shows the AV magnitude (mean, sigma, 90% and 99%).

The information in Table 1 corresponds to the current “reference” tour containing 10 close gravity-assist satellite flybys. The reference tour trajectory is used for orbit determination and maneuver statistical analyses and for tour science planning. During the tour, delivery errors at the satellite flybys cause trajectory dispersions, and it is necessary to reoptimize the tour trajectory in order to minimize total AV and propellant consumption. Otherwise, the limited amount of propellant remaining at the start of the tour would quickly be exhausted. The trajectory optimization process, which varies all remaining satellite aimpoints to minimize total tour AV, must accommodate various constraints. The changes in the satellite aimpoints are limited to ± 50 km (B-plane components) and ± 3 min (closest approach time) with respect to the values of the reference tour. The latest time at which a satellite aimpoint can be changed is at the post-encounter OTM of the previous encounter. Both these constraints serve to limit the amount of rework to the sequences that will be loaded on the spacecraft to perform the science observations. Certain geometrical conditions, such as satellite occultations and

nontargeted encounter altitudes are also constrained. In essence, each trajectory reoptimization during the satellite tour defines a new reference tour trajectory. Trajectory reoptimization software tools have been developed using both a numerically integrated trajectory model and a linearized trajectory model.

An important quantity which affects mission options and navigation strategy is propellant margin (PM). PM is the amount of propellant remaining at the end of the 10-encounter tour at the 90% probability level. Propellant margin is calculated based on spacecraft propulsion system characteristics, various mission ground rules, and the 90% value of AV required to complete the mission (i. e., achieve the 10th satellite encounter). Examples of propulsion system characteristics are the thrust levels of the 10- and 400-Newton engines and their I_{sp} s (~270 sec and ~309 sec, respectively). Examples of mission ground rules affecting PM are the pre-JOI Io flyby altitude (1000 km), the initial perijove radius (4.0 R_J), and the size of the allowed satellite aimpoint changes mentioned above. The 90% mission AV depends strongly on the OD capability during the tour shown in Table 2. Currently, propellant margin is about 15 kg (prior to arrival at Jupiter). As uncertain events, such as the Io flyby, JOI, and the satellite encounters, are completed, PM is recomputed based on the new reference trajectory that results from each trajectory reoptimization.

Figure 1
GALILEO VEEGA INTERPLANETARY TRAJECTORY

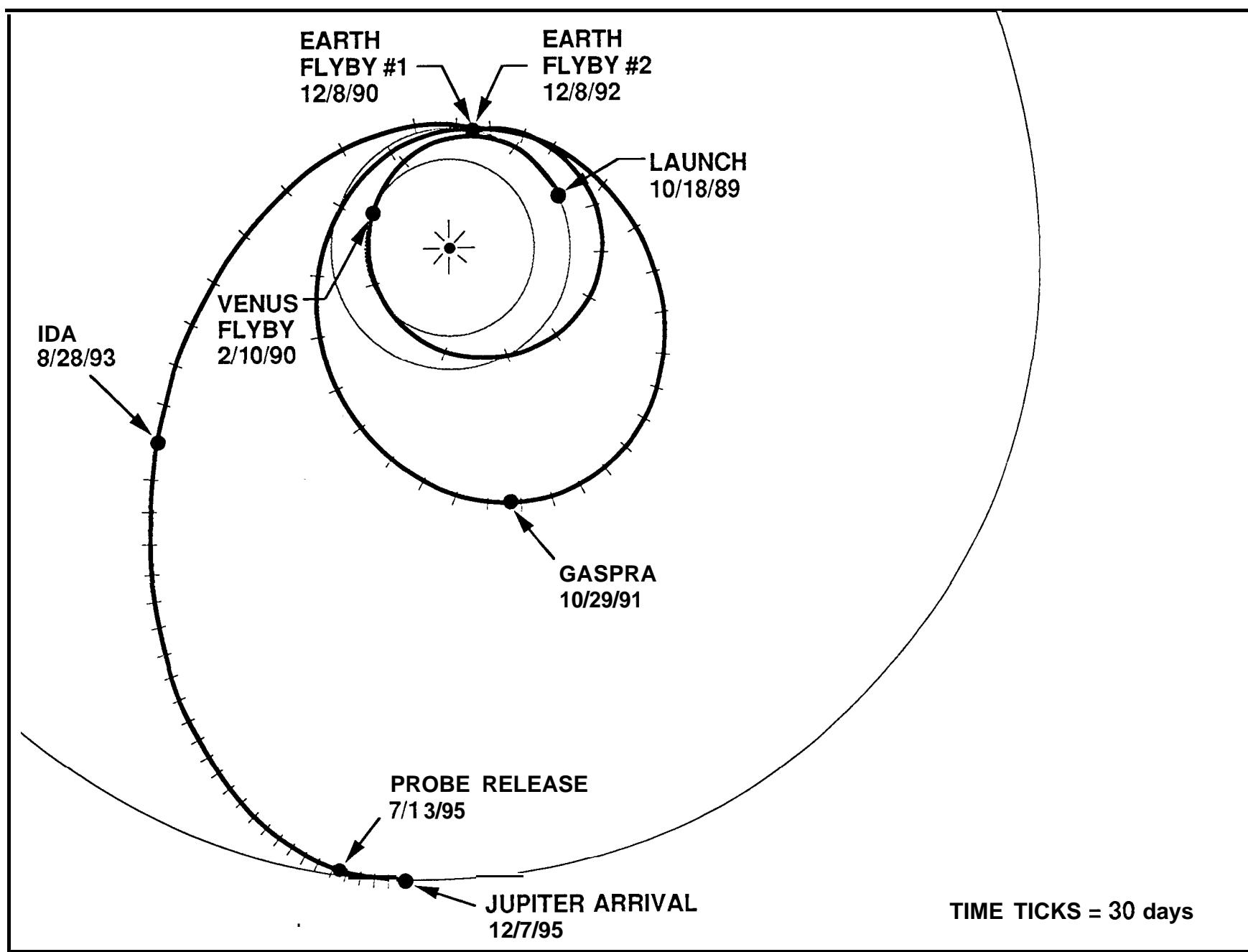


Figure Z

JUPITER ARRIVAL (12/7/95)

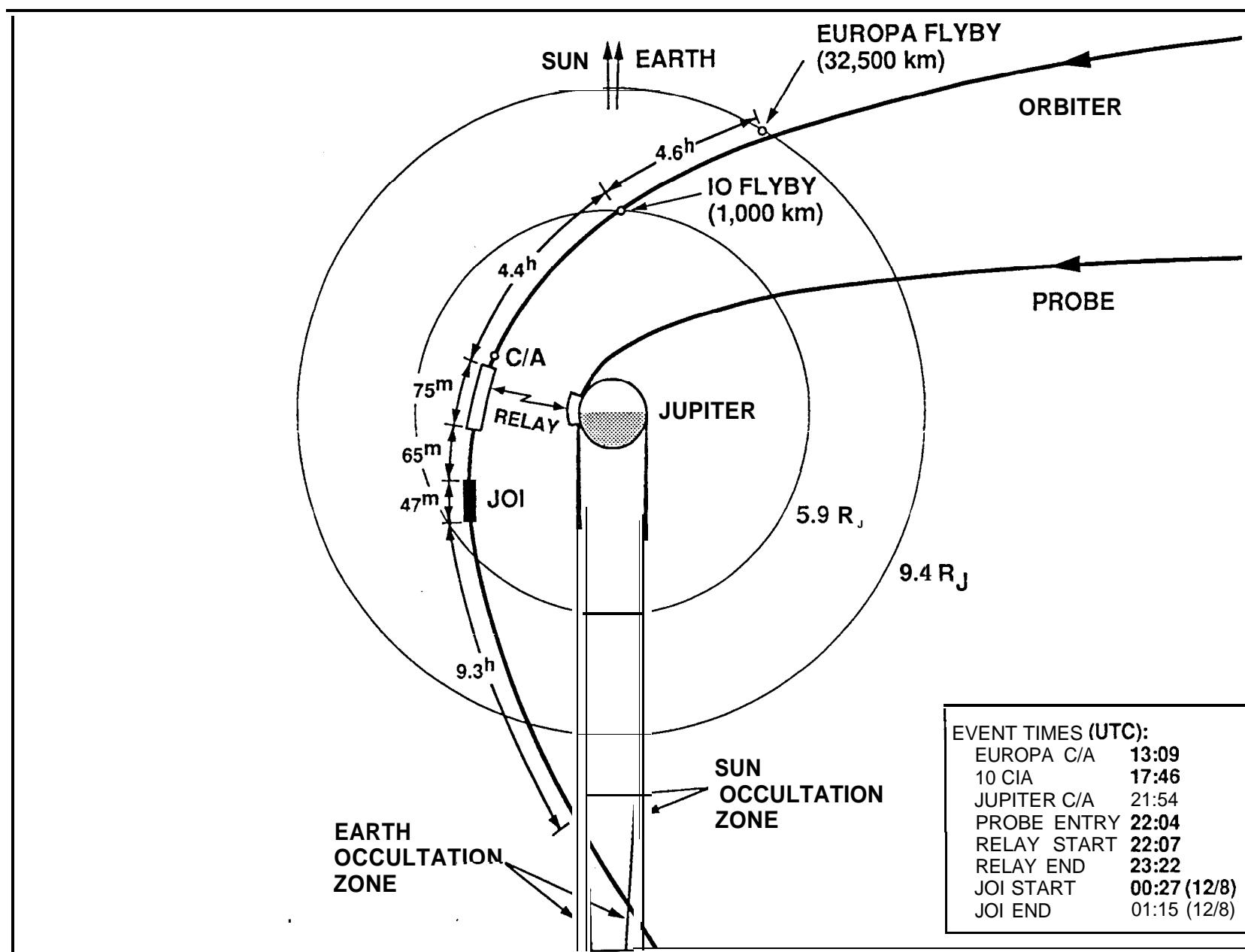


Figure 3

PROBE DESCENT PROFILE

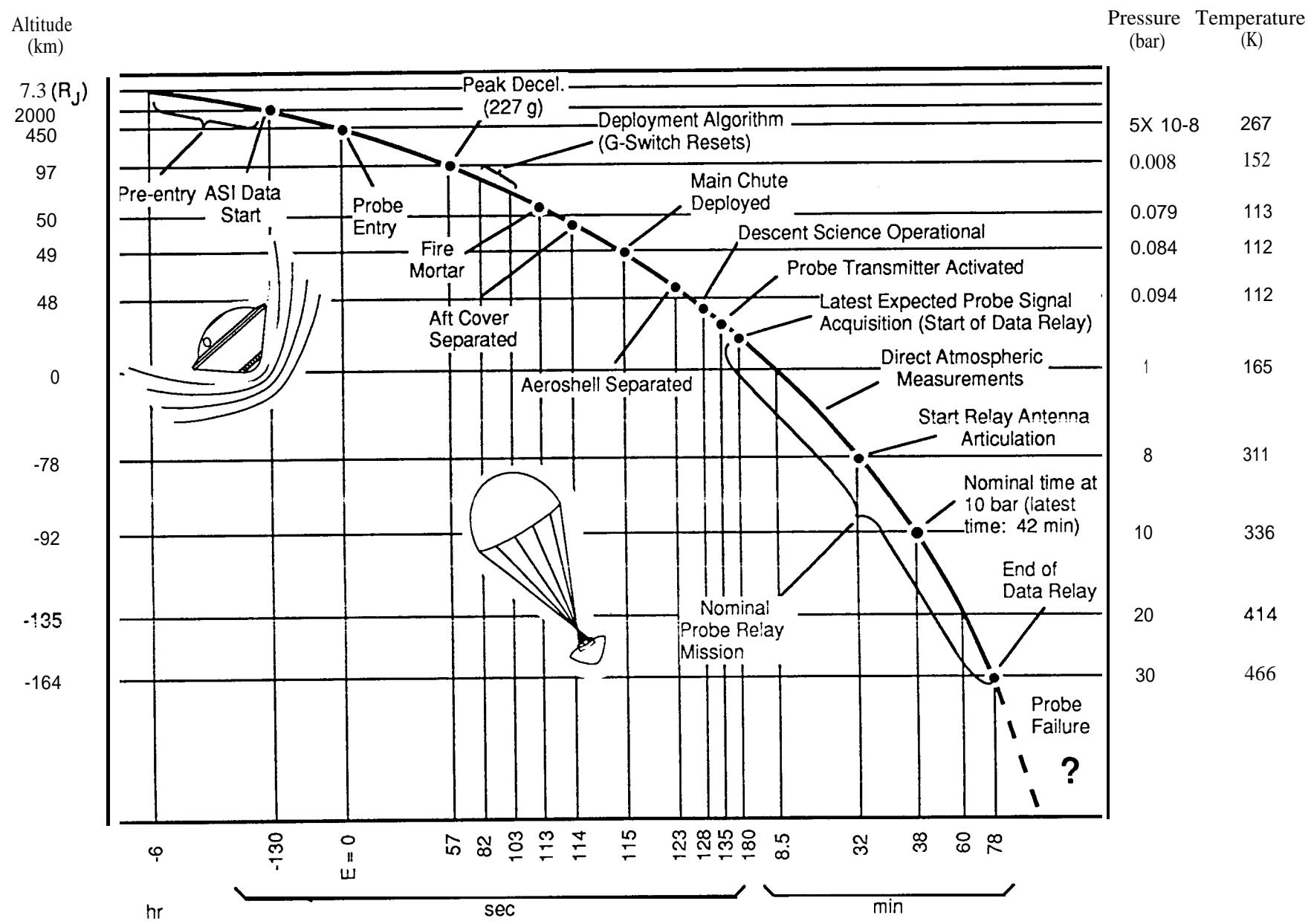


Figure 4
ORBITAL
GALILEO [REDACTED] TOUR

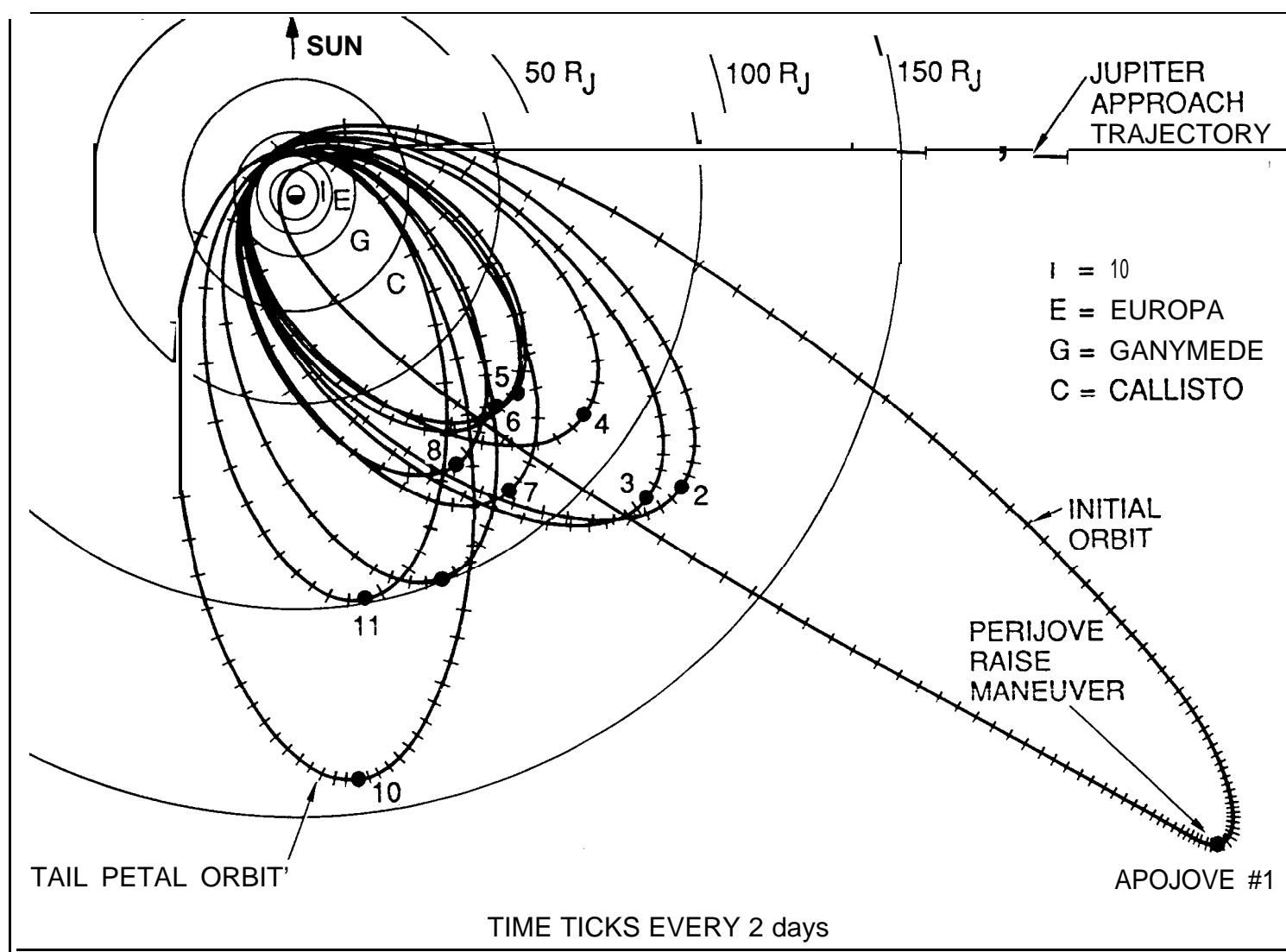


Figure 5
Galileo Spacecraft

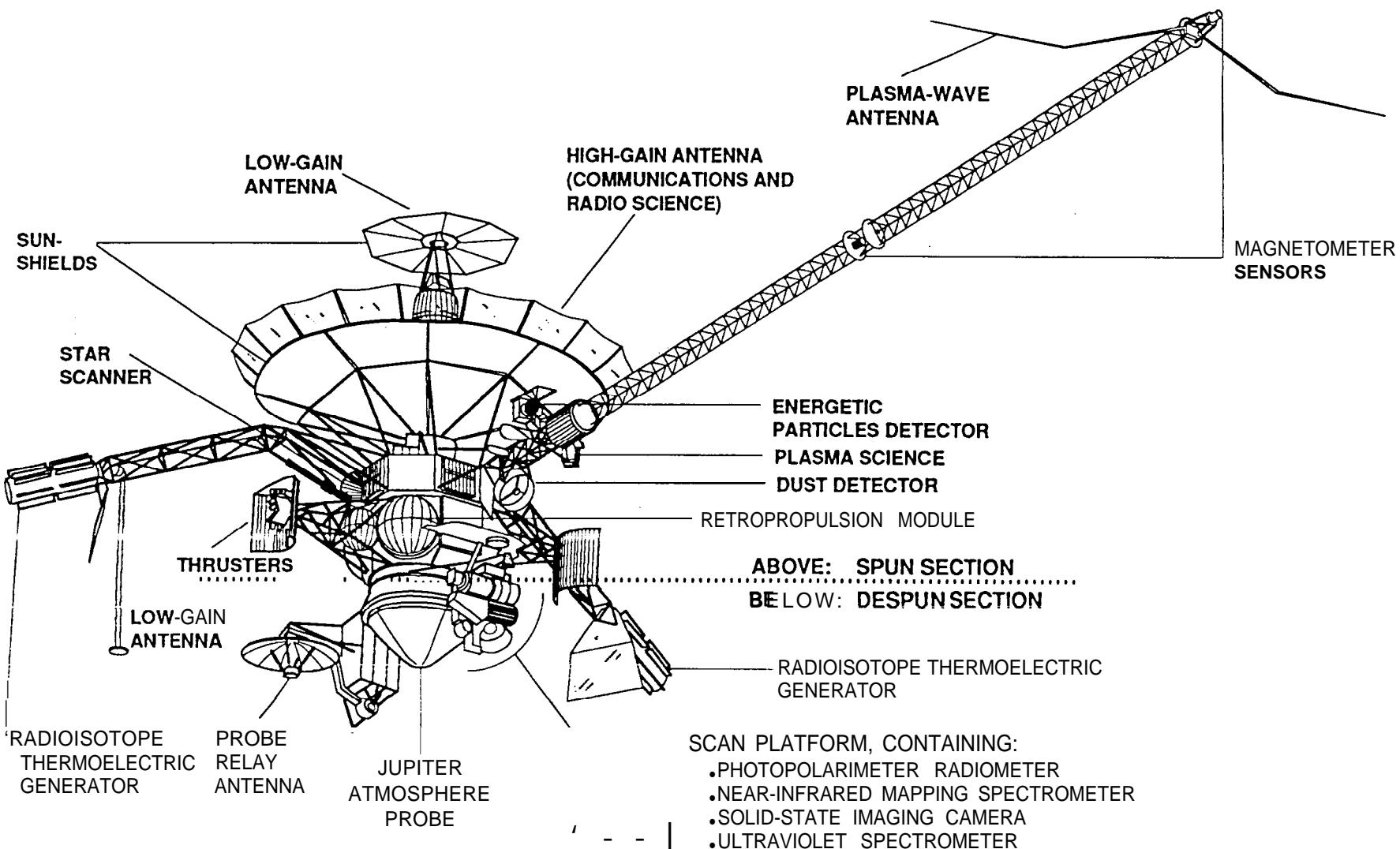
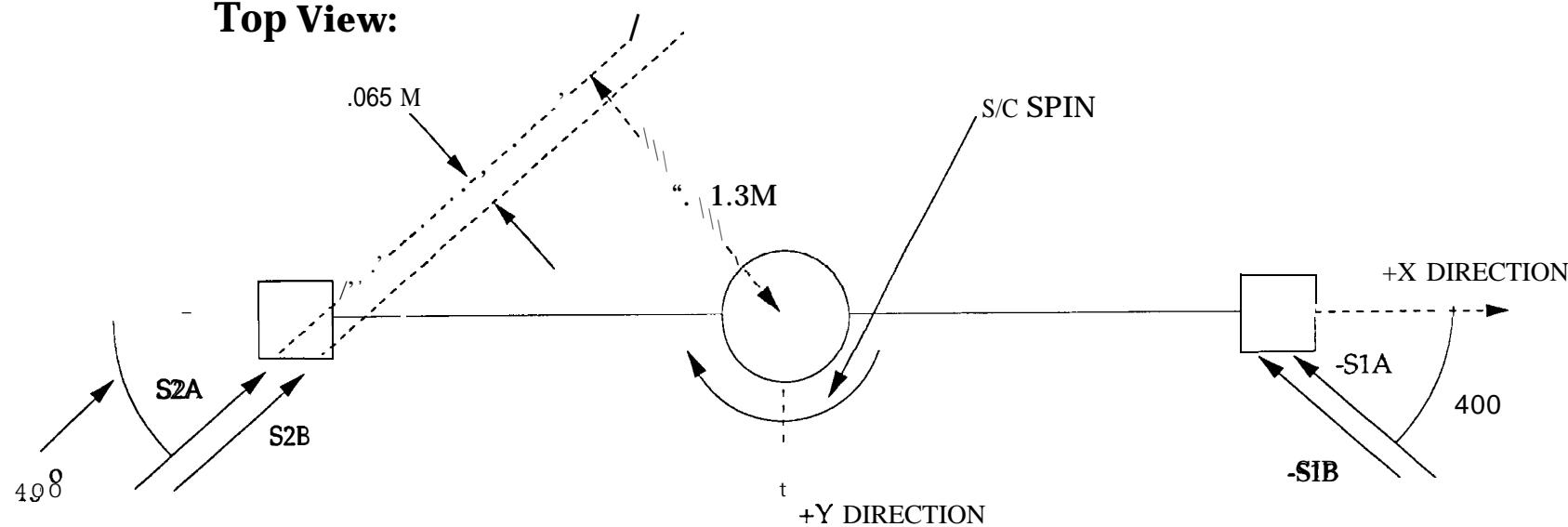


Figure b

Top View:



Side View:

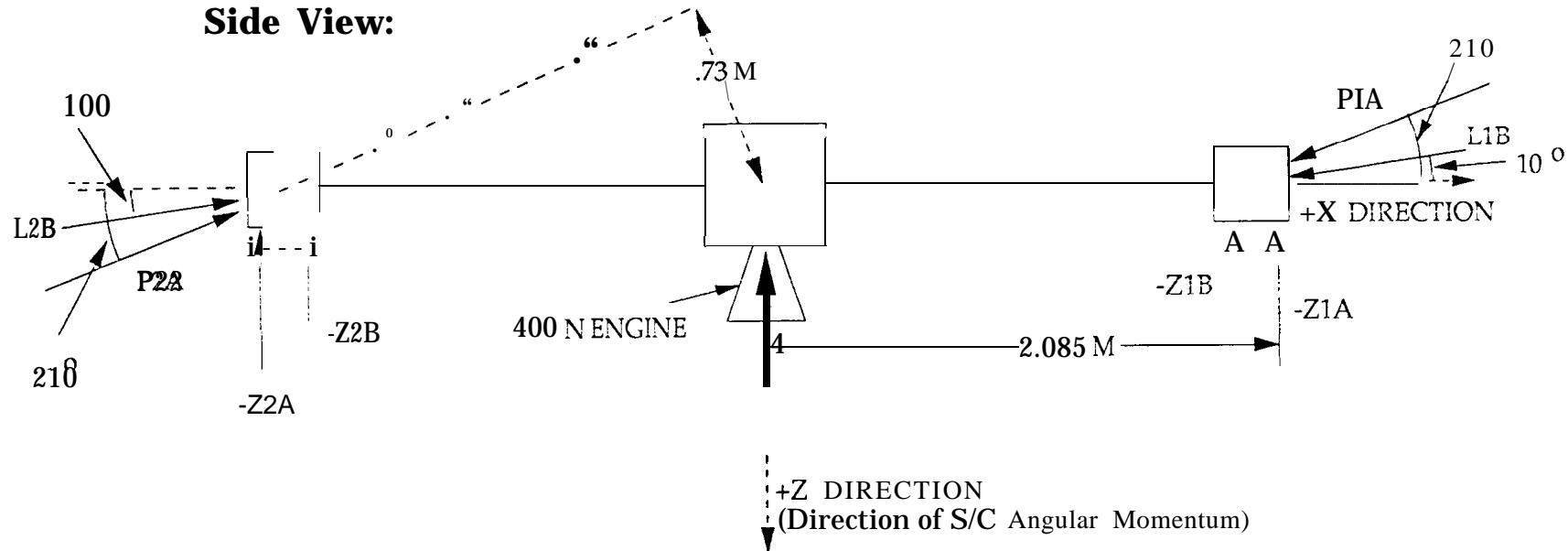


Table 1

Galileo Orbital Tour

Encounter	Date (UTC)	Satellite	Inbound/ Outbound	Altitude (km)	Latitude (deg)	Objective
G1	4 Jul 96	Ganymede	In	500	25	Wake, Alven wing, UVS, gravity, reduce period
G2	6 Sep 96	Ganymede	In	255	85	Alven wing, gravity, reduce inclination
C3	4 Nov 96	Callisto	In	1100	13	Wake, Alven wing, UVS counter-rotate for atmospheric coverage, Jupiter occultations (Sun, Earth)
E3A	6 Nov 96	Europa	out	31947	0	Coverage (232 deg W. Long., phase= 34 deg)
E4	19 Dec 96	Europa	out	695	0	Wake, Europa occultations (Sun, Earth), Jupiter occultations (Sun, Earth)
(E5A)	20 Jan 97	Europa	out	27419	-1	Occurs during solar conjunction interval on phasing orbit
E6	20 Feb 97	Europa	In	588	-17	Europa occultations (Sun, Earth), Jupiter occultations (Sun, Earth), Io occultation
E7A	4 Apr 97	Europa	In	23244	2	Coverage (133 deg W. Long., phase =52 deg), distant wake
G7	5 Apr 97	Ganymede	out	3065	56	Alven wing
C8A	6 May 97	Callisto	In	33499	-42	Coverage (72 deg W. Long., phase= 43 deg)
G8	7 May 97	Ganymede	In	1584	29	Ganymede occultations (Sun, Earth), Jupiter occultations (Earth), distant UVS
C9	25 Jun 97	Callisto	In	416	2	Callisto occultations (Sun, Earth), Jupiter occultations (Earth), Io occultations, tail pets!
G9A	26 Jun 97	Ganymede	In	79961	0	Coverage (98 deg W. Long., phase = 20 deg), distant wake
Tail Petal Apojove	8 Aug 97					143 RJ, 175 deg phase, 0.2 deg inclination
C10	17 Sep 97	Callisto	In	524	5	Wake, Alven wing, Jupiter occultations (Sun, Earth), rotate, UVS, reduce period
E11	6 Nov 97	Europa	In	1119	66	Alven wing

Deterministic AV: JOI = 643 m/s, PJR = 376 m/s, Tour =23 m/s

Total Radiation = 123 krad

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Table 2

**1σ PRE-ENCOUNTER MANEUVER OD incorporating PREVIOUS FLYBY DATA
S-Band Doppler and Reduced Opnav Schedule**

OTM	OD CUTOFF	B.R (kilometers)	B.T (kilometers)	LFT (seconds)	No. of Opnavs total (target)
OTM-6t	G1 - 4d	10.3	17.8	1.1	22 (14) ---
OTM-9	G2 - 17d	19.4	38.3	4.1	14 (8)
OTM-10	G2 - 8d	8.8	10.8	1.4	17 (9)
OTM-10t	G2 - 3d	4.2	3.0	0.2	4.5 (21)
OTM-13	C3 - 12d	19.2	30.2	1.3	6 (5)
OTM-13t	C3 - 4d	15.2	23.6	0.9	21 (14)
OTM-16	E4 - 12d	9.0	17.5	7.1	9 (5)
OTM-16t	E4 - 4d	7.0	3.8	1.3	22 (11)
OTM-20	E6 - 12d	12.6	4.0	1.3	3 (2)
OTM-20t	E6 - 4d	7.7	2.8	0.9	17 (12)
OTM-23	G7 - 12d	48.6	17.0	0.9	3 (3)
OTM-23t	G7 - 5d	13.6	13.9	0.6	14 (6)
OTM-26	G8 - 12d	9.3	19.0	0.7	2 (2)
OTM-26t	G8 - 4d	5.6	17.4	0.2	14 (5)
OTM-29	C9 - 12d	13.7	9.7	1.0	4 (0)
OTM-29t	C9 - 3d	11.0	8.5	0.9	27 (17)
OTM-32	C10 - 12d	9.6	3.8	0.5	5 (0)
OTM-32t	C10 - 4d	9.2	2.9	0.3	22 (13)
OTM-35	E11 - 12d	30.9	9.0	3.4	0
OTM-35t	E11 - 4d	9.2	5.8	1.9	22 (16)

t = maneuver design tweak

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Table 3 TCM AV: Magnitude of Commanded AV

TCM/OTM Number	TCM/OTM Name	Determinist, AV (m/s)	Mean ΔV (m/s)	1σ (m/s)	AV(90) (m/s)	ΔV(99) (m/s)
TCM-19	Ida-172 days	0.0	2.1	0.0		2.1
TCM-20	Ida-15 days	0.0	0.5	0.1	0.6	0.8
TCM-21	Ida-2 days	0.0	0.5	0.3	0.9	1.2
	Ida Flyby	0.0	3.1	0.3	3.5	3.9
TCM-22	Ida+37 days	38.7	38.3	0.2	38.6	38.9
TCM-22A	Jupiter-660 days	0.0	0.5	0.3	(0.9	1.4
TCM-23	Jupiter-239 days	0.0	0.1	0.1	0.2	0.3
TCM-24	Jupiter-167 days	0.0	0.0	0.0	(0.1	0.1
	Probe Separation	38.7	42.1	0.5	42.7	43.4
TCM-25	ODM	58.4	58.4	0.0	56.4	58.4
TCM-26	10-100 days	0.0	0.2	0.1	0.4	0.7
TCM-27	10-20 days	0.0	0.8	0.5	1.6	2.4
TCM-28	Io-10 days	0.0	0.3	0.2	0.5	0.7
TCM-28A	Io-5 days	0.0	0.4	0.2	0.7	0.9
	10 Flyby	97.1	102.2	1.0	103.5	104.9
TCM-29	JOI	645.2	645.1	5.4	652.0	657.5
	Post-JOI	742.3	747.3	5.5	754.0	760.3
OTM-1	OTM-1	0.0	5.4	4.7	12.3	19.1
OTM-2	OTM-2	0.0	1.6	2.7	5.4	11.5
OTM-3	PJR	374.8	374.4	1.2	375.4	376.1
	Post-PJR	1117.1	1128.6	7.3	1138.4	1147.3
OTM-4	PJR + 54 Days	0.0	0.7	0.4	1.2	1.7
OTM-5	G1 -30 Days	0.0	0.1	0.1	0.1	0.3
OTM-6	G1 -3 Days	0.0	0.4	0.2	0.8	1.2
	Ganymede 1	1117.1	1129.8	7.3	1139.4	1148.1
OTM-7	G1+5 Days	0.0	8.2	6.8	18.2	29.9
OTM-8	G1+ Apo	4.8	4.6	0.8	5.3	8.0
OTM-9	G2 -3 Days	0.0	0.8	0.5	1.5	2.4
	Ganymede 2	1121.9	1143.4	10.4	1157.1	1175.9
OTM-10	G2+5 Days	0.0	7.6	6.7	17.2	29.4
OTM-11	G2 + Apo	0.8	1.2	1.1	2.6	5.6
OTM-12	C3 -3 Days	0.0	0.5	0.3	0.8	1.3
	Callisto 3	1122.7	1152.7	13.1	11703	1189.3
OTM-13	C3 + 3 Days	0.0	2.0	1.8	4.2	8.2
OTM-14	C3 + Apo	0.0	2.4	1.1	3.9	5.2
OTM-15	E4 -3 Days	0.0	0.5	0.3	0.8	1.5
	Europa 4	1122.7	1157.5	13.5	1175.1	1193.0
OTM-16	E4 + 3 Days	0.0	3.5	2.7	7.3	11.5
OTM-17	E4 + Apo	0.0	0.8	0.7	1.7	3.0
OTM-18	Orbit 5 Apo	0.0	0.8	0.6	1.6	3.0
O-I-M-19	E6 -3 Days	0.0	0.6	0.4	1.1	1.8
	Europa 6	1122.7	1163.2	13.8	1181.9	1201.2
OTM-20	E6 + 3 Days	0.0	0.9	0.9	2.1	3.4
OTM-21	E6 + Apo	16.7	13.6	1.3	15.3	16.8
OTM-22	G7 -3 Days	0.0	2.1	1.3	3.8	6.4
	Ganymede 7	1139.4	1179.8	13.9	1197.8	1217.0
OTM-23	G7 + 3 Days	0.0	2.3	1.9	5.0	8.4
OTM-24	G7 + Apo	0.0	0.3	0.4	0.7	2.4
OTM-25	G8 -3 Days	0.0	0.3	0.2	0.5	0.8
	Ganymede 8	1139.4	1182.7	14.1	1201.4	1219.7
OTM-26	G8 + 3 Days	0.0	3.6	2.9	7.6	13.0
OTM-27	G8 + Apo	0.2	0.6	0.4	1.2	2.0
OTM-28	C9 -2 Days	0.0	0.3	0.1	0.4	0.7
	Callisto 9	1139.6	1187.1	14.4	1206.2	1226.6
OTM-29	C9 + 3 Days	0.0	2.4	1.8	5.0	7.7
OTM-30	C9 + Apo	0.1	0.5	0.4	0.9	1.7
O-I-M-31	C10 -3 Days	0.0	0.3	0.2	0.5	0.9
	Callisto 10	1139.7	1190.3	14.7	121.03'	1229.8
OTM-32	C10 + 3 Days	0.0	3.3	2.5	6.8	11.0
OTM-33	C10 + Apo	0.3	3.0	1.7	5.3	8.2
OTM-34	E11 -3 Days	0.0	0.5	0.3	0.8	1.3
	Europa 11	1140.0	1197.0	15.2	1218.5	1237.4

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Table 4: TCM Delivery Accuracy

TCM/OTM Number	TCM/OTM Name	Target Body	1 σ b•R (km)	1 σ b•T (km)	1 σ LFT (sec)
TCM-19	Ida-172 days	Ida	415	434	37
TCM-20	Ida-15 days	Ida	56	40	4
TCM-21	Ida-2 days	Ida	11	8	4
	Ida Flyby	Jupiter, Probe	15652	36467	4450
TCM-22	Ida+37 days	Jupiter, Probe	1640	41258	1250
TCM-22A	Jupiter-660 days	Jupiter, Probe	2250	1314	119
TCM-23	Jupiter-239 days	Jupiter, Probe	335	98	28
TCM-24	Jupiter-167 days	Jupiter, Probe	313	89	25
	Probe Separation		10		
TCM-25	ODM	10	241	1876	146
TCM-26	Io-100 days	Io	640	900	66
TCM-27	10-20 days	Io	52	297	23
TCM-28	Io-10 days	Io	4 2	193	15
TCM-28A	10-5 days	10	41	71	6
	Io Flyby	Ganymede 1	315104	5.61E+06	784793
TCM-29	JOI	Ganymede 1	159002	2.83E+06	395913
	Post-JOI	Ganymede 1	7.96E+08	2.73E+10	3.33E+09
OIM-1	OTM-1	Ganymede 1	29991	531569	74520
OIM-2	OTM-2	Ganymede 1	23843	417575	58767
OTM-3	PJR	Ganymede 1	536	7023	1049
	Post-PJR	Ganymede 1	1.95E+06	6.69E+07	8.17E+06
OTM-4	PJR + 54 Days	Ganymede 1	50	190	89
OTM-5	G1-30 Days	Ganymede 1	43	95	83
OTM-6	G1 -3 Days	Ganymede 1	13	25	82
	Ganymede 1	Ganymede 2	8733	299157	36535
OTM-7	G1+5 Days	Ganymede 2	336	6469	893
OTM-8	G1 + Apo	Ganymede 2	40	208	47
OTM-9	G2 -3 Days	Ganymede 2	20	15	36
	Ganymede 2	Callisto 3	1427	201312	20379
OTM-10	G2+5 Days	Callisto 3	249	4108	563
OTM-11	G2 + Apo	Callisto 3	46	105	109
OTM-12	C3 -3 Days	Callisto 3	24	33	108
	Callisto 3	Europa 4	214	42586	16907
OTM-13	C3 + 3 Days	Europa 4	105	5701	1859
OTM-14	C3 + Apo	Europa 4	76	84	77
OTM-15	E4 -3 Days	Europa 4	74	17	73
	Europa 4	Europa 6	8062	416949	141479
OTM-16	E4 + 3 Days	Europa 6	200	6599	2242
OTM-17	E4 + Apo	Europa 6	79	743	382
OTM-18	Orbit 5 Apo	Europa 6	90	40	105
OTM-19	E6 -3 Days	Europa 6	5	8	103
	Europa 6	Ganymede 7	415	30998	4471
OTM-20	E6 + 3 Days	Ganymede 7	413	6135	936
OTM-21	E6 + Apo	Ganymede 7	86	530	96
OTM-22	G7 -3 Days	Ganymede 7	.34	80	82
	Ganymede 7	Ganymede 8	3634	1833	3480
OTM-23	G7 + 3 Days	Ganymede 8	92	954	195
OTM-24	G7 + Apo	Ganymede 8	33	79	83
01%4-25	G8 -3 Days	Ganymede 8	37	46	83
	Ganymede 8	Callisto 9	1544	113761	10951
OTM-26	G8 + 3 Days	Callisto 9	256	1572	277
OTM-27	G8 + Apo	Callisto 9	84	26	109
OTM-28	C9 -2 Days	Callisto 9	84	21	109
	Callisto 9	Callisto 10	4230	280965	29309
OTM-29	C9 + 3 Days	Callisto 10	129	3663	452
OTM-30	C9 + Apo	Callisto 10	86	58	108
OTM-31	C10 -3 Days	Callisto 10	88	36	109
	Callisto 10	Europa 11	1564	139886	65379
OTM-32	C10 + 3 Days	Europa 11	422	2502	1759
OTM-33	C10 + Apo	Europa 11	43	50	30
OTM-34	E11 -3 Days	Europa 11	10	7	3